

Searching for new physics in Upsilon decays *

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Abstract

We examine some possible experimental consequences of new physics on the spectrum and decays of bottomonium states below $B\bar{B}$ threshold. In addition to lepton universality breaking in Upsilon decays, large widths of pseudoscalar η_b resonances and mixing with a non-standard CP-odd light Higgs boson might smooth and shift the signal peak from hindered radiative M1 transitions between Υ and η_b states in the photon energy spectrum, as searched by CLEO. We also stress the relevance of forthcoming results from CLEO on leptonic branching fractions of Υ resonances to definitely check our hypothesis.

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The possibility of new physics showing up in leptonic decays of bottomonium was examined in [1, 2]. There we advocated the existence of a non-standard (CP-odd) light Higgs boson (denoted as A^0) mediating the annihilation of the Upsilon vector resonance into a lepton pair through an intermediate η_b^* state subsequent to a magnetic dipole (M1) transition yielding a soft (unobserved) final-state photon. Then an “apparent” breaking of lepton universality¹ would appear since the Higgs-mediated contribution would be unwittingly ascribed to the leptonic decay channel in the experimental measurement (notably in the tauonic mode because of the employed missing-energy technique) thereby inducing a dependence of the branching fraction (BF) on the leptonic species.

Hitherto, we have assumed in our theoretical analysis that the A^0 mass was close to the bottomonium resonances below $B\bar{B}$ threshold; thus the Higgs propagator in the diagram of Fig.1b should enhance the decay rate ultimately implying moderate values of the parameter $\tan\beta$ - defined as the ratio of the Higgs vacuum expectation values in a two Higgs doublet model (2HDM) [3] - to account for the postulated new physics effect in Υ leptonic decays. In this Letter we relax this condition to some extent, moreover exploring the experimental consequences of our conjecture on bottomonium spectroscopy and hindered radiative transitions from Υ resonances in view of the current failure to detect the $\eta_b(1S)$ and $\eta_b(2S)$ states [4, 5]. Admittedly, the lack of such experimental observation in itself can be hardly used as an argument in favor of new physics, but nonetheless one should keep an open mind in connection with the ideas developed in this work.

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¹In the sense that once the Higgs contribution were taken into account, lepton universality would be restored

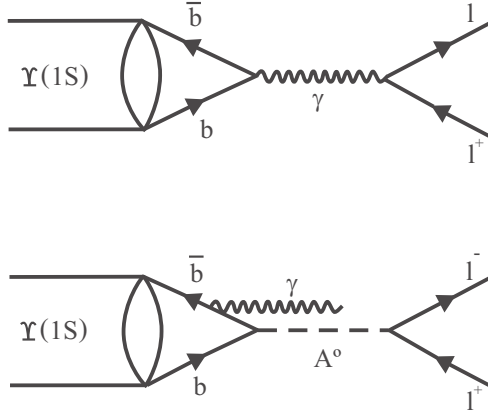


Figure 1: (a)[upper panel]: Electromagnetic annihilation of a $\Upsilon(1S)$ resonance into a charged lepton pair through a virtual photon; (b)[lower panel]: Hypothetical annihilation of an intermediate η_b^* state (subsequent to a M1 structural transition yielding a soft photon) into a charged lepton pair through a CP-odd Higgs particle denoted by A^0 .

In order to assess the relative importance of the postulated new physics contribution, we defined in [1, 2] the BF's ratio:

$$\mathcal{R}_\ell = \frac{\mathcal{B}_{\Upsilon \rightarrow \gamma_s \ell \ell}}{\mathcal{B}_{\Upsilon \rightarrow \ell \ell}} \quad ; \quad \ell = e, \mu, \tau \quad (1)$$

where $\mathcal{B}_{\Upsilon \rightarrow \gamma_s \ell \ell}$ and $\mathcal{B}_{\Upsilon \rightarrow \ell \ell}$ refer to the Higgs-mediated and standard electromagnetic contributions to the Υ leptonic decay, respectively. Focusing on the tauonic channel, $\mathcal{B}_{\Upsilon \rightarrow \gamma_s \tau \tau}$ was estimated as the “excess” $\mathcal{B}_{\Upsilon \rightarrow \tau \tau} - \mathcal{B}_{\Upsilon \rightarrow \ell \ell}$ with either $\ell = e, \mu$ from available experimental data [6]; thereby \mathcal{R}_τ was found to be of order 10% in both $\Upsilon(1S)$ and $\Upsilon(2S)$ decays although with a considerable experimental uncertainty [1, 2]. Nevertheless, we performed a hypothesis test concluding that lepton universality (predicting $\mathcal{R}_\tau = 0$) could be rejected at a 10% level of significance.

Two theoretical approaches were used in [1] to deal with the $\Upsilon \rightarrow \gamma_s \ell \ell$ decay. Firstly, we applied time-ordered perturbation theory considering a two-step process: a prior M1-transition yielding a $b\bar{b}$ pseudoscalar virtual state followed by its annihilation into a lepton pair mediated by the A^0 (see Fig.1b). Alternatively, we relied on the separation between long- and short-distance physics in accordance with the main lines of a non-relativistic effective theory like NRQCD [7], albeit replacing a gluon by a photon in the usual Fock decomposition of hadronic bound states. Different results for the final widths come out in each approach, as we shall see below (see [1] for a lengthier discussion).

On the one hand, factorization à la NRQCD [7] of the decay width leads to

$$\Gamma_{\Upsilon \rightarrow \gamma_s \ell \ell} = \mathcal{P}^\Upsilon(\eta_b^* \gamma_s) \times \Gamma_{\eta_b^* \rightarrow \ell \ell} \quad (2)$$

where $\mathcal{P}^\Upsilon(\eta_b^* \gamma_s)$ denotes the probability for a Fock component in the $\Upsilon(nS)$ ($n = 1, 2, 3$) resonance containing an almost on-shell η_b^* state and a soft photon γ_s ; in Refs.[1, 2] this probability was estimated by means of the well-known formula connecting $\Upsilon(nS)$ and $\eta_b(nS)$ states through a direct M1-transition:

$$\mathcal{P}^\Upsilon(\eta_b^* \gamma_s) \approx \frac{\Gamma_{\Upsilon \rightarrow \gamma_s \eta_b}^{M1}}{\Gamma_\Upsilon} \simeq \frac{1}{\Gamma_\Upsilon} \frac{4\alpha Q_b^2}{3m_b^2} \Delta E_{hs}^3 \sim 10^{-5} - 10^{-3} \quad (3)$$

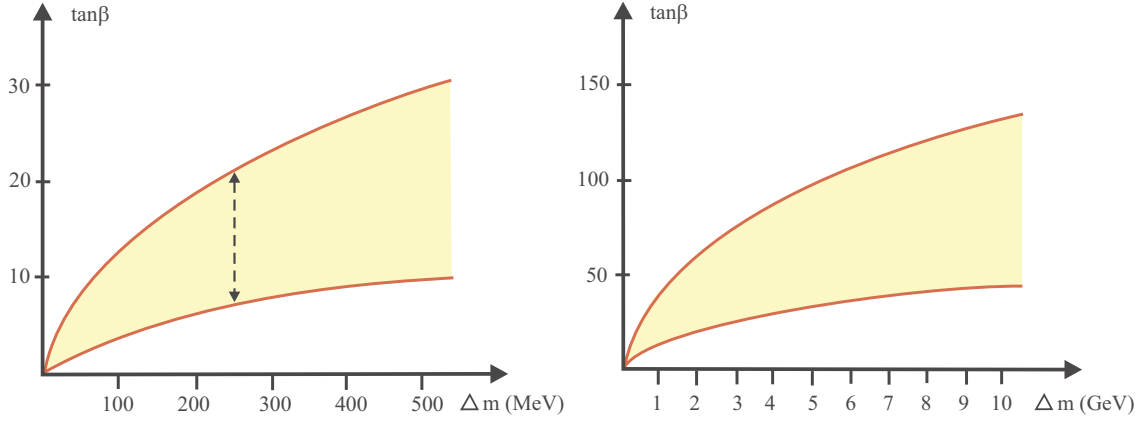


Figure 2: Required $\tan\beta$ values (shaded area) needed to account for a $\sim 10\%$ breakdown of lepton universality in Υ decays as a function of Δm according to the factorization (4). The vertical dotted line shows the range of $\tan\beta$ for $\Delta m = 250$ MeV used in [1] as a reference value.

where Γ_Υ stands for the resonance full width, $\alpha \simeq 1/137$ denotes the fine-structure constant, $Q_b = 1/3$ is the bottom-quark electric charge and $m_b = M_\Upsilon/2 \simeq 5$ GeV; we took the hyperfine $\Upsilon - \eta_b$ mass splitting ΔE_{hs} varying over the broad range $35 - 150$ MeV. Note that the intermediate η_b^* state actually should not be too far off-shell because of the small photon energy given by ΔE_{hs} . So we will not distinguish between η_b and η_b^* hereafter; besides η_b denotes collectively any $\eta_b(nS)$ ($n = 1, 2, 3$) state though we have focused on the $\eta_b(1S)$ because of currently more precise data on the leptonic BF of the $\Upsilon(1S)$ [6].

Thus, the final decay width for the whole process can be re-expressed from Eq.(2) as

$$\Gamma_{\Upsilon \rightarrow \gamma_s \ell \ell} \simeq \frac{\Gamma_{\Upsilon \rightarrow \gamma_s \eta_b}^{M1}}{\Gamma_\Upsilon} \Gamma_{\eta_b \rightarrow \ell \ell} \quad (4)$$

By requiring the BF's ratio \mathcal{R}_τ in Eq.(1) to be of order 10%, we found in [1] that $\tan\beta$ in a 2HDM(II) has to stay over the range: $7 \lesssim \tan\beta \lesssim 21$, depending on the value of ΔE_{hs} , namely from 150 MeV down to 35 MeV. Actually this $\tan\beta$ interval corresponds to a particular choice of the Higgs mass value, in between the $\Upsilon(1S)$ and $\Upsilon(2S)$ masses. Here we relax somewhat this condition: Fig.2 shows the $\tan\beta$ -range as a function of Δm , defined as the mass difference between the postulated non-standard Higgs and the $\eta_b(1S)$ resonance [1]. For the largest values of Δm only the lower area of the shaded region would be likely acceptable - corresponding to the highest estimates of $\mathcal{P}^\Upsilon(\eta_b^* \gamma_s)$ in (3).

On the other hand, applying second-order time perturbation theory instead of the factorization given by Eq.(2), one obtains that the partial width of the whole decay, in the narrow width approximation (i.e. $\Gamma_{\eta_b}/2 \ll \Delta E_{hs}$), reduces to

$$\Gamma_{\Upsilon \rightarrow \gamma_s \ell \ell} \simeq \Gamma_{\Upsilon \rightarrow \gamma_s \eta_b}^{M1} \frac{\Gamma_{\eta_b \rightarrow \ell \ell}}{\Gamma_{\eta_b}} \quad (5)$$

In fact this equation matches a cascade decay taking place via the aforementioned η_b^* intermediate state. Let us remark that Eqs.(4) and (5) are numerically (and conceptually) quite different as one expects $\Gamma_\Upsilon \ll \Gamma_{\eta_b}$. Thus, in general, $\tan\beta$ values higher than in the previous approach are required in order to account for the same $\mathcal{O}(10\%)$ breakdown

of lepton universality, while the Higgs mass value has to be kept below $B\bar{B}$ threshold to enhance the decay rate through the Higgs propagator as already mentioned.

Now, since the Higgs-mediated partial width of the leptonic decay of the η_b state depends on the fourth power of $\tan\beta$ and the leptonic mass squared (see Eq.(20) of Ref.[1]), a large value of the former quantity would imply that the pseudoscalar resonance (which stands below open bottom production) would mainly decay through the tauonic channel, i.e.

$$\Gamma_{\eta_b} \simeq \Gamma_{\eta_b \rightarrow \tau\tau} \quad (6)$$

overwhelming all other decay modes. For example, if $\tan\beta \gtrsim 35$ the full width turns out to be $\Gamma_{\eta_b} \gtrsim 30$ MeV in contrast with the expected $\Gamma_{\eta_b} \simeq 4$ MeV obtained from the asymptotic expression $\Gamma_{\eta_b} \simeq m_b/m_c \times [\alpha_s(m_b)/\alpha_s(m_c)]^5 \times \Gamma_{\eta_c}$, setting $\Gamma_{\eta_c(1S)} = 16 \pm 3$ MeV [6]².

Then from Eqs. (5) and (6), the partial width for the tauonic channel approximately coincides with the M1-transition width, i.e.

$$\Gamma_{\Upsilon \rightarrow \gamma_s \tau\tau} \simeq \Gamma_{\Upsilon \rightarrow \gamma_s \eta_b}^{M1} \quad (7)$$

because of the almost complete cancellation of the partial and full widths of the η_b . Next, dividing both sides of the above approximate equality by the Υ full width, one finds

$$\mathcal{B}_{\Upsilon \rightarrow \gamma_s \tau\tau} \simeq \frac{\Gamma_{\Upsilon \rightarrow \gamma_s \eta_b}^{M1}}{\Gamma_{\Upsilon}} \quad (8)$$

As $\mathcal{B}_{\Upsilon \rightarrow \tau\tau} \sim 10^{-2}$ [6], the value of the BF's ratio \mathcal{R}_{τ} of Eq.(1), calculated according to the above expression (8), can indeed reach a 10% order-of-magnitude for the highest estimates from Eq.(3). This result represents a step forward in our investigation using this approach with respect to Ref.[1]. Thus, a large η_b width (e.g. $\Gamma_{\eta_b} \gtrsim 30$ MeV) could stem either from (4), or from the alternative factorization (5), for high $\tan\beta$ in both cases.

Let us observe that quite broad pseudoscalar $b\bar{b}$ resonances might explain why there is no evidence found from hindered M1 radiative decays of higher Upsilon resonances into $\eta_b(1S)$ and $\eta_b(2S)$ states in the search performed by CLEO [4, 5]. The corresponding signal peak (which should appear in the photon energy spectrum) could be considerably smoothed - in addition to the spreading from the experimental measurement - and thereby might not be significantly distinguished from the background (arising primarily from π^0 's). Of course, the matrix elements for hindered transitions are expected to be small and difficult to predict as they are generated by relativistic and finite size corrections. Nevertheless, most of the theoretical calculations (see a compilation in Ref.[10]) are ruled out by CLEO results (at least) at 90% CL, though substantially lower rates are obtained in [11] where exchange currents play an essential role and therefore cannot be currently excluded. Let us finally point out that a large full width of the η_b resonance would bring negative effects on the prospects for its detection at the Tevatron through the double- J/ψ decay: $\eta_b \rightarrow J/\psi + J/\psi$. Indeed, the expected BF would drop by about one order of magnitude with respect to the range between 7×10^{-5} and 7×10^{-3} assumed in [12].

Furthermore, another interesting possibility is linked to a $A^0 - \eta_b$ mixing [13] which could sizeably lower the mass of the mixed (physical) η_b state, especially for high $\tan\beta$

²Let us stress that there are still open windows for relatively light non-standard Higgs masses and moderate $\tan\beta$ values, still not ruled out by direct searches at LEP [8, 9]. Also notice that for a meaningful existence of the pseudoscalar state, the η_b full width should remain smaller than the $\Upsilon - \eta_b$ hyperfine splitting

values starting from similar masses of the unmixed states [1]. Then the signal peak in the photon energy plot could be (partially) shifted off the search window used by CLEO [4, 5] towards higher γ energies (corresponding to a smaller η_b mass³) perhaps contributing additionally to the failure to find evidence about the existence of the η_b resonances to date. As a particular but illustrative example, assuming for the masses of the unmixed states $m_{\eta_{b0}} \simeq m_{A_0^0} = 9.4$ GeV and the moderate $\tan \beta = 20$ value, one gets for the physical states $m_{A^0} = 9.56$ GeV and $m_{\eta_b} = 9.24$ GeV respectively⁴.

On the other hand, CLEO has completed detailed scans of the $\Upsilon(nS)$ ($n = 1, 2, 3$) resonances and we want to stress the relevance of these measurements (aside many other applications) for testing more accurately the possible existence of new physics by a more precise determination of the electronic, muonic and tauonic BF's of *all three* resonances below open bottom threshold. In case no lepton universality breaking is definitely found, some windows in the $\tan \beta$ - m_{A^0} parametric space for such a non-standard CP-odd light Higgs boson⁵ would be closed.

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³This would be the case if the (unmixed) CP-odd Higgs boson had a mass greater than the (unmixed) η_b resonance [13]. We work under this hypothesis throughout this paper

⁴The mass formula for the physical A^0 and η_b states in terms of the unmixed states (denoted as A_0^0 and η_{b0} respectively), and the off-diagonal mass matrix element $\delta m^2 \simeq 0.146 \times \tan \beta$ [1], for quite narrow resonances (i.e. $\Gamma_{\eta_{b0}}, \Gamma_{A_0^0} \ll m_{\eta_{b0}}, m_{A_0^0}$) reads [1]:

$$m_{\eta_b, A^0}^2 \simeq \frac{1}{2}(m_{A_0^0}^2 + m_{\eta_{b0}}^2) \mp \frac{1}{2} \left[(m_{A_0^0}^2 - m_{\eta_{b0}}^2)^2 + 4(\delta m^2)^2 \right]^{1/2}$$

which yields in the case of the physical η_b and A^0 particles for different mass intervals:

$$\begin{aligned} m_{\eta_b, A^0} &\simeq m_{\eta_{b0}} \mp \frac{\delta m^2}{2m_{\eta_{b0}}} \quad ; \quad 0 < m_{A_0^0}^2 - m_{\eta_{b0}}^2 << 2 \delta m^2 \\ m_{\eta_b, A^0} &\simeq m_{\eta_{b0}} \mp \frac{(\delta m^2)^2}{2m_{\eta_{b0}}(m_{A_0^0}^2 - m_{\eta_{b0}}^2)} \quad ; \quad m_{A_0^0}^2 - m_{\eta_{b0}}^2 >> 2 \delta m^2 \end{aligned}$$

⁵Likewise, other scenarios and models can be considered, e.g., Higgs bosons with no defined CP [14]

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